

The use of satellite and surface observations for initializing clouds in the HARMONIE NWP model

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Abstract

The study tests and further develops a previously presented method for adjusting initial clouds in the HARMONIE mesoscale numerical weather prediction (NWP) model. The method uses satellite-observed cloud properties from the Nowcasting and very short range forecasting Satellite Application Facility (NWCSAF) together with ground-based synoptic stations (SYNOP) observations, adjusting the humidity profile of the model based on the available cloud information with the overall aim to improve the forecast, in particular as regards clouds and solar radiation. A reference set-up of the HARMONIE model is used as a baseline against which the cloud initialization experiments are compared. All HARMONIE experiments are run for July 2016, with a model run starting at 06Z each day. The HARMONIE outputs are compared with cloud fraction and solar radiation observations from ground-based stations, while satellite cloud observations are also used for inspecting the behaviour of the forecasts. The performance of other generally used verification parameters is also studied. The results as regards clouds are encouraging. Symmetrical extremal dependence index (SEDI) skill scores show improvement in initial cloud conditions in 84% and 74% of the cases, when evaluated for cloud-free (0–1 octas) and cloudy conditions (7–8 octas), respectively. The improvement lasts 2–4 hr into the forecast. Other parameters, however, show somewhat degraded skill as compared with the reference model run, while for solar radiation, the cloud initialization scheme exhibits somewhat ambiguous results. The distribution of solar radiation values is improved for relatively sunny conditions, while at the other end of the distribution, the cloud initialization scheme produces too many cases with relatively strongly attenuated radiation.

KEYWORDS

cloud initialization, data assimilation, HARMONIE, meteorology, nowcasting, numerical weather prediction (NWP), NWCSAF, solar radiation

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1 | INTRODUCTION

The world is currently shifting from largely coal and oil-based energy production to using increasingly renewable energy. Because of its strong dependence on the prevailing weather conditions, renewable energy production is often intermittent by its nature. This poses a key challenge for future energy systems: How to integrate efficiently variable renewable energy sources into the energy network, enabling the optimal use of available energy resources. As regards solar energy production, this calls for improved weather predictions in terms of clouds and solar radiation.

Numerical weather prediction (NWP) models constitute the backbone of modern weather forecasting. Although such models have been increasingly used for solar energy forecasting in recent years, they still have a relatively short history, being scrutinized in terms of their performance as regards solar radiation and solar energy production. Furthermore, clouds constitute the single most important parameter with regard to solar radiation and solar energy forecasts, and they are known to be difficult to predict accurately (e.g. Ahlgrimm and Forbes, 2012; Kosmopoulos *et al.*, 2015; Tuononen *et al.*, 2019). Although a fair amount of progress has been made on how to improve cloud and radiation forecasts by using, for example, satellite-observed clouds, most operational NWP models do not use cloud observations in their data assimilation or model initialization schemes.

A recent review by Kurzrock *et al.* (2018) provides an overview of studies using satellite-based cloud information in the NWP. They divide the presented approaches into two main categories: (1) the assimilation of satellite radiances, which contain information on cloud conditions; and (2) using retrieved cloud properties (e.g. cloud top height, cloud mask) to adjust the initial state of the NWP model to correspond better to real atmospheric conditions. Recent examples of studies belonging to the first category for the convective-scale NWP include Zhang *et al.* (2019), Otkin and Potthast (2019) and Scheck *et al.* (2020). Benjamin *et al.* (2004), Veen (2013), Chen *et al.* (2015) and Meng *et al.* (2019), on the other hand, represent the second category. Note that the second category can be subdivided into studies applying data assimilation on satellite cloud products (e.g. Chen *et al.*, 2015) and those who use other means for adjusting the initial state of the model (e.g. Veen, 2013). Kurzrock *et al.* (2018) find that methods belonging to the first group often do not introduce a strong enough change to the model's initial state. Methods belonging to the second group, in contrast, often aberrate from established data-assimilation approaches, where the process of initializing the model state is carefully balanced. A further outcome of

Kurzrock *et al.* (2018) is that a rather broad spectrum of various approaches exists, and that each approach is strongly tied to the specific NWP model used, including the set of tools that are readily available for that model.

With this in mind, and with the particular aim to produce a fairly strong effect in the present NWP model, we choose to build upon the work of Veen (2013), who used satellite-observed cloud properties together with synoptic cloud observations to adjust the initial cloudiness in the high resolution limited area model (HIRLAM) NWP model. Veen found that the method generally improved the initial HIRLAM clouds when compared with ground-based observations, and that the positive impact was still present 24 hr into the forecast in almost 60% of cases. In the approach, the humidity profile of the model is adjusted based on the cloud base height, determined by interpolating synoptic cloud base observations, and the satellite-based cloud top height. Veen notes that this approach, essentially assuming a one-layer cloud, may cause too thick clouds to be present in the model. Based on the work of Veen, the Swedish Meteorological and Hydrological Institute (SMHI) developed an alternative approach (unpublished) for the handling of the cloud base in which the cloud base height is determined by combining satellite-retrieved cloud-type information with a cloud-base climatology. This approach may have advantages, for example, in areas where synoptic cloud observations are less dense.

The present study uses the HARMONIE-AROME ("HARMONIE") model. The HARMONIE is a non-hydrostatic, convection-permitting model developed through joint efforts of the international ALADIN-HIRLAM consortium (Bengtsson *et al.*, 2017) and used for operational weather forecasting in MetCoOp (Müller *et al.*, 2017), that is, the Meteorological Co-operation on Operational NWP (currently) involving Norway, Sweden, Estonia and Finland.

The aims of the present study are: to evaluate the method of Veen (2013), including the approach developed by the SMHI, in a mesoscale model in Nordic summer conditions; to develop this method further based on the known shortcomings discussed above; and to document the chosen methodology, which is currently used for preoperational nowcasting in MetCoOp.

2 | DATA AND METHODS

2.1 | HARMONIE NWP model and assimilated data

The HARMONIE NWP model (Bengtsson *et al.*, 2017; Frogner *et al.*, 2019) is the central tool in the present

study. We use version 40h1.1.1 with a horizontal resolution of 2.5 km, covering the domain area shown in Figure 1. The HARMONIE is based on a semi-implicit semi-Lagrangian discretization scheme, where subgrid-scale physical processes are parameterized. The default short wave radiation parametrization in the HARMONIE is the Morcrette radiation scheme from the European Centre for Medium-Range Weather Forecasts (ECMWF)-integrated forecast system (IFS), which contains six spectral intervals (0.185–0.25, 0.25–0.44, 0.44–0.69, 0.69–1.1, 1.1–2.38 and 2.38–4.00 μm). The long wave radiation scheme contains 16 spectral bands (between 3.33 and 1,000 μm), where the Rapid Radiative Transfer Model (RRTM) is used (Mlawer *et al.*, 1997). The short and long wave schemes are described in the IFS (ECMWF, 2015) and in the mesoscale research model Meso-NH documentation (Mascart and Bougeault, 2011). In the HARMONIE, the cloud fraction is modelled using a cloud and condensation scheme (i.e. not a prognostic parameter). It is considered that the model resolution is high enough (with 2.5 km horizontal resolution, 65 vertical levels and top boundary at 10 hPa) to resolve the deep convection directly, but the shallow convection is using a parameterization scheme (Bengtsson *et al.*, 2017).

In all the HARMONIE runs, the initial model state was set up using a three-dimensional variational assimilation (3DVAR) scheme with three-hourly cycles (Brousseau *et al.*, 2011). A standard set-up of observations

was used for the assimilation, including balloon soundings, surface synoptic stations (SYNOP), aircraft reports, ship observations, drifting buoys and satellite clear-sky radiances from the advanced microwave sounding unit (AMSU)-A and advanced television infrared observation satellite (TIROS) operational vertical sounder (ATOVS) over the sea. The assimilation of surface variables is performed by applying optimal interpolation for the surface-level parameters: 2 m temperature and relative humidity, and sea surface temperature. This standard set-up is the reference experiment (Ref), to which other experiments are compared. Section 3 describes the set-up of these other HARMONIE experiments.

2.2 | NWCSAF satellite clouds

As outlined in the introduction, the aim is to use satellite-observed cloud information to adjust the initial state of the HARMONIE NWP model. Here we use the cloud products from the Nowcasting and very short range forecasting Satellite Application Facility (NWCSAF) (Gleau, 2016) of the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). The NWCSAF's products are based on the spinning enhanced visible and infrared imager (SEVIRI) onboard the Meteosat Second Generation satellite (Schmetz *et al.*, 2002). The Finnish Meteorological Institute (FMI) is running the NWCSAF software locally to process the satellite data, including the parallax correction (NWCSAF, 2019). The output is available every 15 min, with approximately 8 km resolution over southern Finland (Kwiatkowska *et al.*, 2016), and includes the following parameters used in the present study: cloud fraction (decimal value between 0 and 1), cloud mask (integer value of 0 or 1), cloud type and cloud top temperature. Of these, cloud fraction is used for visual evaluation of the results (see Section 4.1), while the others are used to adjust the initial state of the model.

2.3 | Ground-based observations

The primary data used in the verification of the HARMONIE model experiments are the cloud fraction from the ground-based SYNOP network over the model domain and solar global radiation (short wave downward) from Finland (Figure 1). Global radiation is measured operationally by the FMI using ventilated Kipp and Zonen CM11 secondary standard pyranometers, and the instruments are calibrated yearly or every second year. The present study uses values of hourly global radiation. Based on a more detailed analysis of the Swedish radiation measurement network (Persson, 2000), the

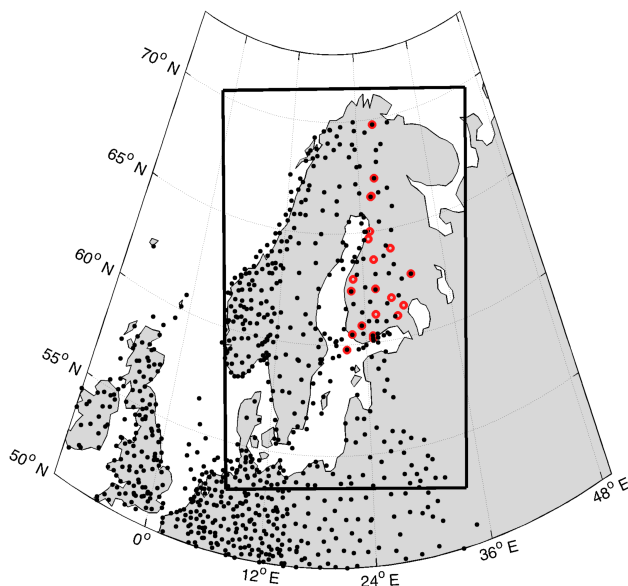


FIGURE 1 HARMONIE model domain (rectangular box) and synoptic stations (SYNOP) stations providing cloud fraction and cloud base height (black dots) together with solar radiation measurement stations over Finland (fuller circles). The availability of SYNOP cloud data may vary with time; the map shows the stations providing cloud data for 1500 UTC on July 30, 2016

uncertainty of these hourly values is estimated to be roughly 4%, except for low solar elevation angles when larger uncertainty is expected.

SYNOP stations are reporting in accordance with the World Meteorological Organization (WMO) standards, and the observation data are distributed in near real-time to the national meteorological services. The SYNOP cloud observations can be human made or produced by automatic stations, where a ceilometer is used to determine the cloud base and cloud fraction. In the latter case, the cloud fraction is inferred from the time during which a cloud is observed in the line of sight of the ceilometer. In the SYNOP observations, the cloud fraction is reported in octas, ranging from 0 to 8, where 0 is cloud free and 8 is fully overcast.

Both the automatic and the manual cloud observations have their characteristic features. The largest differences between the two occur in the tails of the distribution, where manual observations tend to report values of 1/8 and 7/8 more often than automatic ones (Mittermaier, 2012). Ceilometers have a limited field of view compared with the full hemisphere of the manual observations, and ceilometers also lose sensitivity with height, resulting in high clouds not being detected by the automatic stations (Wagner and Kleiss, 2016). From the point of view of testing clouds as represented by a 2.5 km resolution NWP model such as the HARMONIE, the more limited field of view of automatic stations may be rather appropriate. The accuracy of the observed cloud fraction is estimated to be about 1 octa (Boers *et al.*, 2010).

The present study uses the SYNOP cloud base observations to adjust the initial state of the model (Section 3), while the SYNOP cloud fraction, 2 m temperature and humidity are used together with balloon soundings for the verification of our model experiments (Section 4). The cloud fraction observations of the region of interest (Figure 1) are mostly automatic. In Finland, for example, only two out of the 217 SYNOP cloud stations provide manual observations.

2.4 | Verification

All observations used in the verification of the HARMONIE NWP experiments are matched with information from the nearest model grid point. Measured hourly global radiation values are compared with hourly values from the model, while for the other parameters instantaneous model values are used.

Clouds are highly variable in space and time, and the cloud fraction typically follows a strongly non-normal,

'U'-shaped distribution. This means that popular error metrics, such as root mean square error (RMSE), can be misleading. The verification metrics should ideally be independent of the occurrence frequency (Hogan *et al.*, 2009). The symmetric extremal dependence index (SEDI) was used by Chiu *et al.* (2014) and Ferro and Stephenson (2011) for cloud fraction verification. It provides meaningful results for extreme and rare events, that is, when the hit rate and false-alarm rate decrease towards zero. The SEDI scores range from -1 to 1 , where 1 is a perfect skill score and 0 corresponds to a random forecast. The SEDI is calculated based on the hit rate (H) and false-alarm rate (F) from a contingency table containing 2×2 elements (Barnes *et al.*, 2009):

$$\text{SEDI} = \frac{\log F - \log H - \log(1 - F) + \log(1 - H)}{\log F + \log H + \log(1 - F) + \log(1 - H)}$$

For the verification of cloud fraction, we focus on the tails of the distribution by calculating the SEDI for cloud amounts of 1/8 or less (nearly cloud free) and 7/8 or more (nearly overcast). The tails are of particular interest because the initial model clouds are adjusted based on satellite cloud mask. Choosing these thresholds also makes the analysis somewhat less sensitive to differences between manual and automatic cloud observations; at the cloudy side, for example, the largest difference between the automatic and manual cloud fractions occurs on the border between 7/8 and 8/8 (Mittermaier, 2012), which means that including both 7/8 and 8/8 in the nearly overcast group evens out the difference.

We use the HARMONIE verification package (MONITOR) to calculate most of the verification scores used. The MONITOR is a self-contained and stand-alone package using the extracted NWP model and observational data (Xiaohua, 2009; de Rooy and de Vries, 2017). In addition to the SEDI, we also include the bias (BIAS) and standard deviation of the error (STDE) as verification metrics, as also used by Van der Veen (2013):

$$\text{BIAS} = \frac{1}{N} \sum_{i=1}^N (X_i - Y_i) = (X - Y)$$

$$\text{STDE} = \sqrt{\frac{1}{N-1} \sum_{i=1}^N ((X_i - Y_i) - (X - Y))^2}$$

where X is the estimated variable; and Y is the observed variable.

3 | HARMONIE EXPERIMENTAL SET-UP

In all the HARMONIE experiments, the model initial state is first set up using 3DVAR (as explained in Section 2.1). Thereafter, we use cloud information from the NWCSAF satellite product and ground-based SYNOP observations to adjust the cloud field at the starting point of the model forecast. Here we follow the approach of Veen (2013) in which the humidity profile of the model is modified based on the available cloud information.

When a cloud is detected by the satellite, the humidity is set to saturation in the layers between cloud top and cloud base unless the layer is already saturated. The saturation is calculated from temperature and pressure information, at given atmospheric conditions. Additionally, above the cloud top and below the cloud base, the humidity is set to sub-saturation if needed, using the following equations (Veen, 2013):

$$qm = C \times qs$$

where qm is the model-specific humidity; qs is the saturation-specific humidity; and C is calculated as follows:

$$C = RH_{\max} - (RH_{\max} - RH_{\min}) \times \sin\left(\frac{\pi p}{ps}\right)$$

The sub-saturation is determined by the maximum ($RH_{\max}$) and minimum ($RH_{\min}$) critical relative humidities, which are related to when clouds start to form. Here the critical relative humidity is assumed to be highest near the surface and near the tropopause, and lowest in the middle of the troposphere (Molod, 2012; Quaas, 2012). The pressures at levels (p) and at surface (ps) are taken from the NWP model. Also, the humidity is set to sub-saturation in cases where the satellite cloud mask indicates cloud-free conditions, but the model is saturated.

Additionally, above the cloud top and below the cloud base, the humidity is set to sub-saturation if needed. The humidity is set to sub-saturation also in cases where the satellite cloud mask indicates cloud-free conditions and the model is saturated. In order to keep the virtual temperature constant and to preserve the buoyancy (i.e. to avoid instabilities as a result of adding moisture), the temperature profile is adjusted after changing the humidity in an iterative approach described in more detail by Veen (2013) and de Haan and van der Veen (2014).

The essential information needed to adjust the initial model state is cloud mask, cloud top height and cloud

base. The satellite product provides cloud mask and cloud-top temperature. Cloud-top height is then determined by comparing the cloud-top temperature with the model's temperature profile (Gleau, 2016). Two methods are used to estimate the cloud-base height:

- Cloud base method 1: the use of SYNOP cloud-base observations horizontally interpolated, with a weighting factor proportional to the minus sixth power of the distance to cover the area of interest (Veen, 2013).
- Cloud base method 2: based on the satellite-detected cloud type, the cloud base is set to a specific predefined value derived from climatological information from Mesan (Häggmark *et al.*, 2000), a mesoscale analysis system in operational use by the SMHI. The predefined values are based on empirical data over a long time series, where the situational cloud type (from satellite information) is correlated to the existing cloud base of the MESAN analysis. There are predefined cloud base values for 14 different cloud types, for example, a low stratiform cloud is set to have a cloud base at 550 m.

The HARMONIE NWP model was run for July 2016 at the ECMWF High Performance Computer (HPC) facilities. Forecasts starting at 06Z each day and extended to +9 hr were produced. The starting point of 06Z is 4–5 hr before solar noon in Finland. We altogether run four different model experiments:

- Reference (Ref): Standard set-up of the HARMONIE.
- Experiment 1 (Exp1): Cloud mask and cloud top from the NWCSAF and cloud base method 1.
- Experiment 2 (Exp2): Cloud mask and cloud top from the NWCSAF and cloud base method 2, following the method previously developed by the SMHI.
- Experiment 3 (Exp3): As for the Exp2, but with the following modifications (Figure 2):
- We exclude the NWCSAF cloud type classes with high semi-transparent thin clouds and fractional sub-pixel water clouds. This is performed in order to avoid adding clouds that are considered to be uncertain and potentially give an excessive amount of clouds.
- A new scheme was added taking into account saturation towards both water and ice. Whereas previously the scheme only calculated saturation towards water, we here use a temperature-based combination of saturation towards water and ice. For temperatures > 253.16 K, saturation towards water is used; and for temperatures < 223.16 K, saturation towards ice is used. Between these temperatures, a linearly weighted average of the two is used.
- Inclusion of a cloud-forming sensitivity scheme that allows humidity to be added to the model only in the

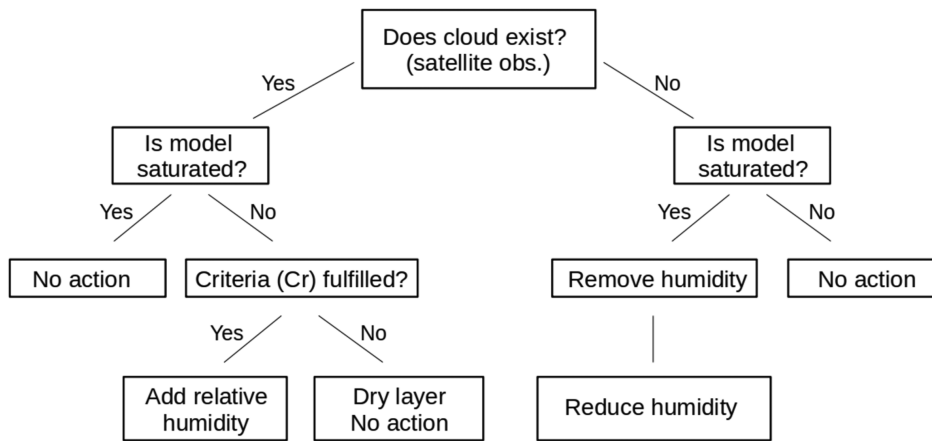


FIGURE 2 Flowchart for the Exp3 method

case the model is already reasonably close to start forming clouds. At each grid point and level, the NWP model's initial humidity is compared with a threshold value, Cr (Equation 4). If the threshold is met or exceeded, then humidity is added. Otherwise, the humidity stays unchanged (i.e. the layer stays cloud free because the model indicates dry conditions). Cr is defined as:

$$Cr = \left(\frac{(P + 166600)}{333300} \right) \times 100$$

where P is pressure (Pa). The Cr is a drier threshold than C . The idea of Cr is to avoid adding excessive amounts of clouds, especially in the case of large vertical distance between cloud top and base, for which we have seen problems with too thick and opaque clouds. The formula is based on initial information from Quaas (2012) and the authors' own trials. Figure 2 shows a flow chart of the method used in the Exp3.

4 | RESULTS

Section 4.1 presents the results for the cloud fraction, including a case study comparing the NWP model clouds with satellite observations. Such a visual inspection is useful as it reveals details not captured in the verification scores. Section 4.2 discusses solar radiation verification, while Section 4.3 describes the skill scores of other meteorological parameters.

4.1 | Cloud fraction

Figures 3 and 4 show the mean SEDI skill scores for cloud-free and cloudy conditions, respectively. During

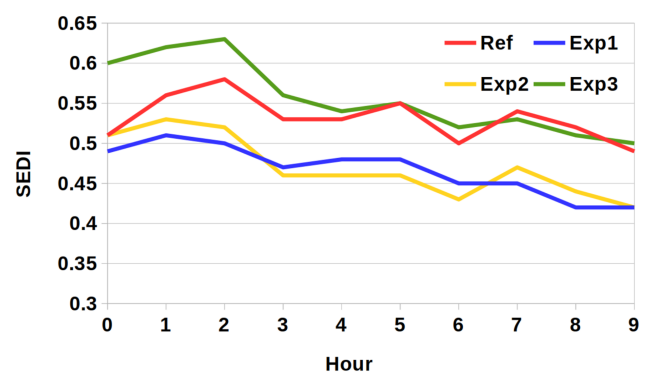


FIGURE 3 Verification of the cloud fraction 0–1 octas (i.e. cloud free) using the symmetrical extremal dependence index (SEDI): Ref (red), Exp1 (blue), Exp2 (yellow) and EXP3 (green) for July 2016, with a lead-time of 9 hr and start at 06Z daily

the first 2–4 hr of forecast, the Exp3 exhibits better scores than the Exp1, the Exp2 and Ref; in cloud-free conditions (Figure 3), the Ref and Exp3 show similar scores for +4 hr and onward, while for cloudy conditions (Figure 4), the Ref is better than the Exp3 already from +2 hr onward. A separate analysis including some of the best cases (largest improvement in the SEDI) shows that, also in these cases, the positive impact typically fades away within 2–4 hr.

Figure 5 presents the SEDI scores of the initial cloud fraction of the Ref and Exp3, for all model runs included in the present study (July 2016). The Exp3 in general improves the initial cloud fraction of the model. For cloud-free conditions, the Exp3 has a better SEDI in 84% of the runs, while for cloudy conditions the Exp3 is better than the Ref in 74% of the runs.

The standard verification scores (BIAS and STDE in Figure 6) for cloud fraction show that the Exp3 is better on average than the Ref during the first hours (up to 4 hr). At longer lead times, the Exp3 and Ref have a similar BIAS, while the Exp1–2 have the worst scores during the

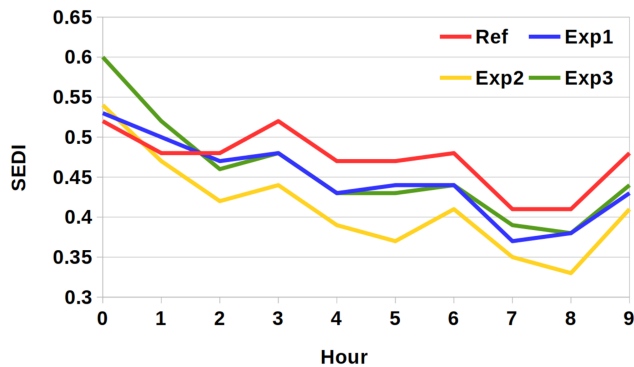


FIGURE 4 Verification of the cloud fraction 7–8 octas (i.e. cloudy) using the symmetrical extremal dependence index (SEDI): Ref (red), Exp1 (blue), Exp2 (yellow) and Exp3 (green) for July 2016, with at lead-time of 9 hr and start at 06Z daily

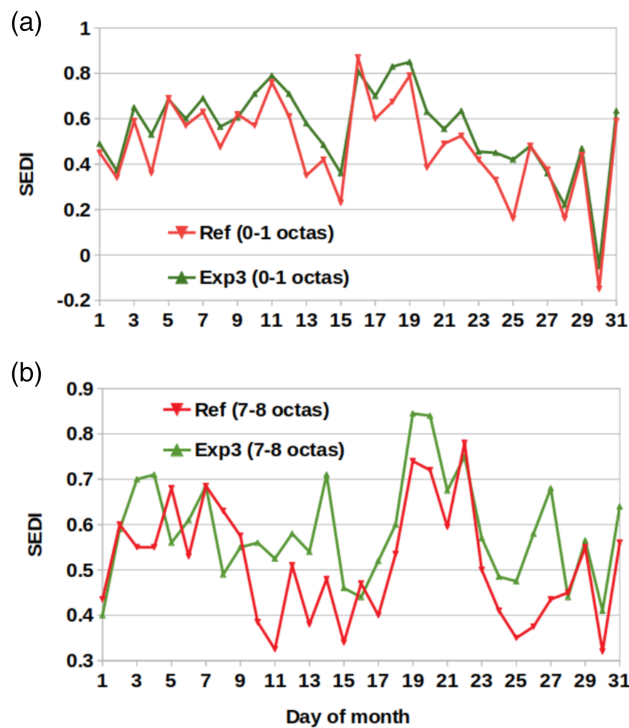


FIGURE 5 Verification of the initial condition of cloud fraction forecast in July 2016: (a) 0–1 octas (i.e. cloud-free) and (b) 7–8 octas (i.e. cloudy); Ref (red); and Exp3 (green)

whole period (Figure 6a). The Ref has the highest STDE during the first hour, but becomes similar to the Exp1–3 already after 1 hr into the forecast (Figure 6b).

Satellite images from the METEOSAT-9 High Resolution Visible channel are used for validation in order to interpret the HARMONIE cloud fraction with real satellite imagery. The details in the cloud pattern are improved for the Exp3 (Figure 7, right) compared with the Ref (Figure 7, middle) and the reality as seen in

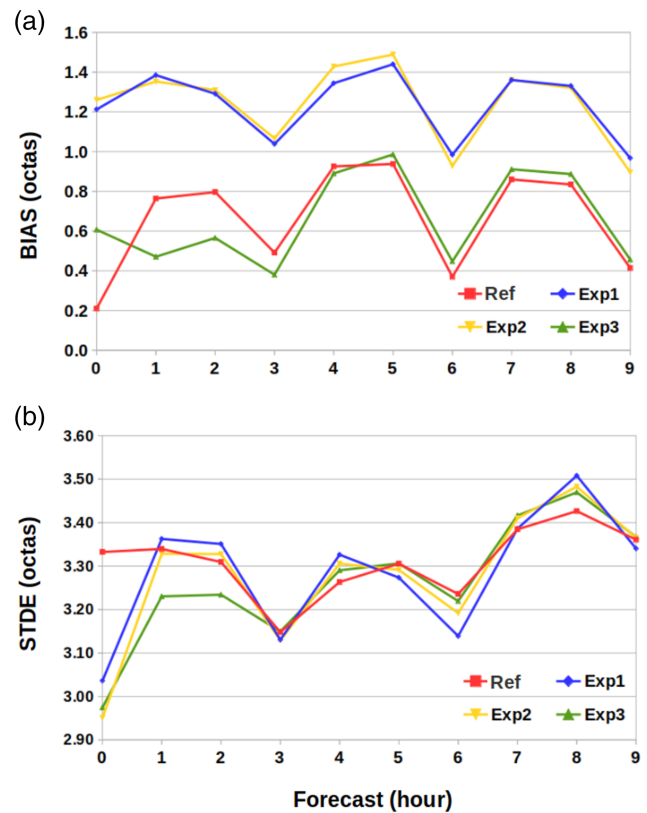


FIGURE 6 Standard verification metrics: (a) bias (BIAS) and (b) the standard deviation of the error (STDE) for cloud fraction (octas) for July 2016 and model start at 06Z daily, with forecasts out to 9 hr. Lines refers to Ref (blue), Exp1 (red), Exp2 (yellow) and Exp3 (green)

satellite image (Figure 7, left), for 0600 UTC on July 21, 2016. In the Ref, the clouds over middle-to-south Sweden are more scattered, while in the Exp3 these are better represented and positioned. The Ref gives too large cloud-free area east of the Gulf of Finland when compared with the satellite clouds. This area is better captured in the Exp3, where cloudiness is increased and in better agreement with satellite information. The corrections do persist and in the +3 hr forecast and one can see that the Exp3 still has a generally better cloud pattern (Figure 8). The Exp3 shows better SEDI scores than the Ref in these cases (Figures 7 and 8) for both cloud-free (0–1 octas) and cloudy (7–8 octas) situations. In case humidity is being removed from the model initial state, the Exp3 is not always able to remove all the excessive clouds that exist in the Ref, and in some cases (with humid surroundings) the clouds may form again after a short time. For example, in an area around Vaasa on the Finnish west coast, clouds still prevail in the Exp3 although the satellite observations indicate largely cloud-free conditions.

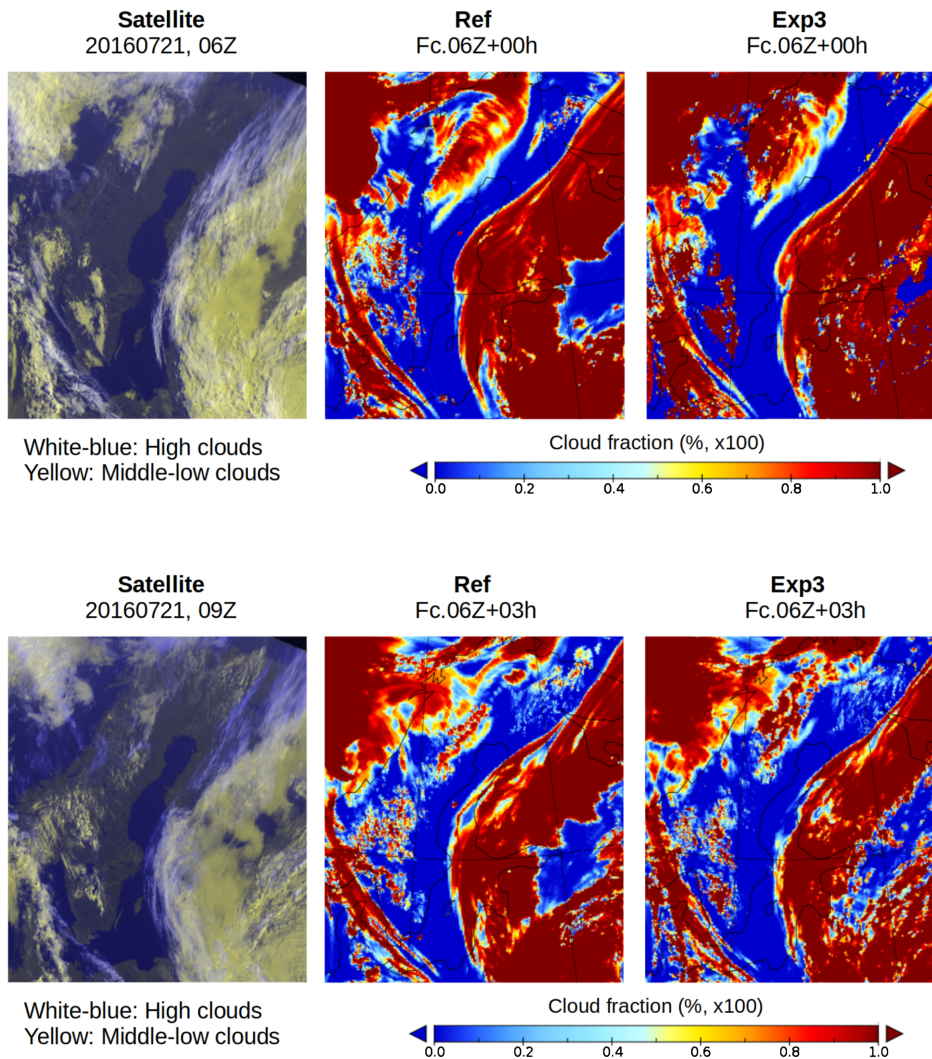


FIGURE 7 Visual inspection of the cloud conditions as depicted by the Meteosat satellite (left), Ref (middle) and Exp3 (right), for 0600 UTC on July 21, 2016, and forecast time +00 hr using symmetrical extremal dependence index (SEDI) skill scores: Ref (0–1 octas) = 0.49, Ref (7–8 octas) = 0.59, Exp3 (0–1 octas) = 0.56 and Exp3 (7–8 octas) = 0.67

FIGURE 8 Visual inspection of the cloud conditions as depicted by the Meteosat satellite (left), Ref (middle) and Exp3 (right), at 0900 UTC on July 21, 2016, and forecast time +03 hr using symmetrical extremal dependence index (SEDI) skill scores: Ref (0–1 octas) = 0.49, Ref (7–8 octas) = 0.64, Exp3 (0–1 octas) = 0.62 and Exp3 (7–8 octas) = 0.66

4.2 | Solar radiation

The solar radiation (global short wave downwelling) from the HARMONIE output was verified against 21 Finnish stations (here only results from the Ref and Exp3 are shown). Figure 9 shows the BIAS and STDE for the Ref and Exp3. The Exp3 BIAS scores are better, on average, than for the Ref (Figure 9a), while the STDE is slightly higher for the Exp3 compared with the Ref (Figure 9b).

From radiation histograms of forecasts with lead-time + 1 h (i.e. at 0700 UTC daily), one can see that the Ref both underpredicts (too high frequency of low-valued radiation) and overpredicts (too high frequency of high-valued radiation) the solar radiation in the first hour of the forecasts (Figure 10, red compared with black). The most probable reasons for this are: the incorrect placement of the cloud field, too few clouds or too transparent clouds. The Exp3 gives a higher frequency of low-valued radiation (i.e. it overpredicts the occurrence of clouds) compared with both observations and the Ref. On the

other hand, the Exp3 has a better distribution for the high radiation values, where it is closer to observations (Figure 10, blue compared with black). The same tendency can be seen for the intermediate radiation conditions, that is radiation frequencies between 150 and 450 $\text{W}\cdot\text{m}^{-2}$. Here the Exp3 gives higher frequencies of radiation than the Ref for the 150–300 $\text{W}\cdot\text{m}^{-2}$ interval, and less for 300–450 $\text{W}\cdot\text{m}^{-2}$.

4.3 | Other parameters

The surface verification scores (not shown) for mean sea level pressure, 2 m temperature and humidity all become slightly worse for the Exp3 when compared with the Ref in terms of both the BIAS and STDE. The 2 m temperature, for example, is somewhat colder in the Exp3 than in the Ref. While the initial temperature bias is only slightly shifted, from -0.28 to -0.32°C , the Exp3 is 0.15°C colder than the Ref at +2 hr. This

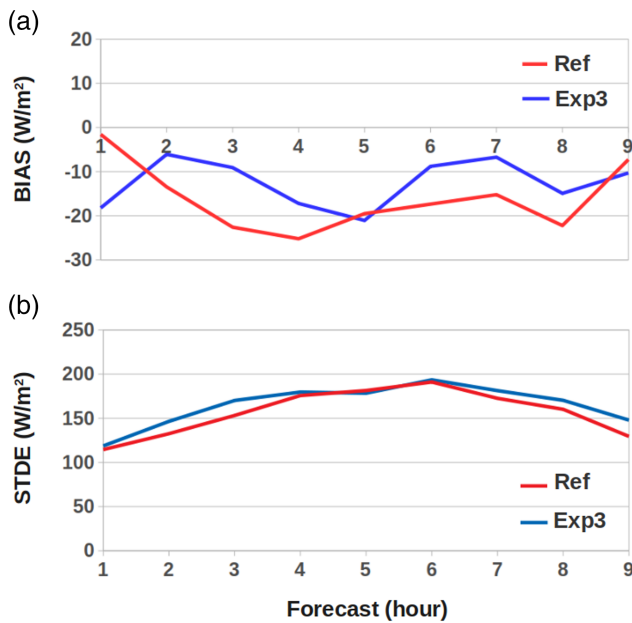


FIGURE 9 Hourly global solar radiation verification scores against Finnish stations for July 2016: (a) bias (BIAS) ($\text{W}\cdot\text{m}^{-2}$); and (b) standard deviation of the error (STDE) ($\text{W}\cdot\text{m}^{-2}$). Forecast out to +9 hr (x-axis), starting at 0600 UTC daily, for Ref (red line) and Exp3 (blue line)

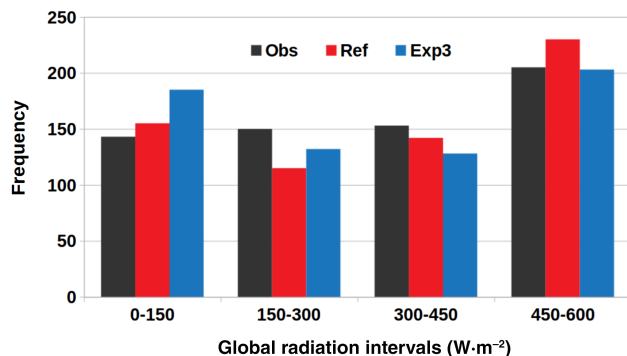


FIGURE 10 Global solar radiation histogram at different radiation intervals for observations (observed; black) and +1 hr forecasts; Ref (red) and Exp3 (blue)

difference then gradually decreases and has essentially disappeared at +8 hr. It is worth noting further that the bias in 2 m temperature of both the Exp1 (initially -0.62°C , reaching -1.2°C at +3 hr) and Exp2 (initially -0.44°C , -0.85°C at +4 hr) is more negative than that of the Exp3.

Also for the upper air, for example, the middle to lower troposphere, the temperature and humidity quality are somewhat degraded in the cloud initialization experiments (again, not shown). Here the BIAS scores are slightly worse for the Exp3 than for the Ref, while the STDE shows similar performance. Furthermore, the Exp1–2 are worse than Exp3, similarly to the results for 2 m temperature.

5 | CONCLUSIONS

The present study tests and further develops a previously presented method for adjusting initial clouds in the HAR-MONIE mesoscale numerical weather prediction (NWP) model in Nordic summer conditions. The method uses satellite-observed cloud properties from the Nowcasting and very short range forecasting Satellite Application Facility (NWCSAF) together with ground-based synoptic stations (SYNOP) observations, adjusting the humidity profile of the model based on the available cloud information with the overall aim to improve the forecast, in particular, as regards clouds and solar radiation.

Two methods used to determine the cloud base height were investigated, as explained in Section 3. Each method has its strengths and weaknesses:

- Cloud base method 1 used in the Exp1: In some situations the method cannot capture the borders between different cloud areas. If, for example, the SYNOP observation is located in an area of low clouds while the nearby area (where no observations are available) contains only high cirrus, then the low cloud base information will be transferred into the cirrus-covered area, effectively increasing the assumed vertical extent of the cloud. Hence, this method would benefit from a dense surface observational network.
- Cloud base method 2 used in the Exp2–3: In this method, the edges, areas and patterns of different clouds are mainly well captured because they are based on satellite observations. However, an inherent feature of the satellite-observed cloud properties is that low clouds below high clouds cannot be properly detected. In such cases, this method may misinterpret multilayer clouds as, for example, high cirrus, hence causing a too high cloud base altitude to be assumed.

Overall, the results show encouraging results as regards clouds. The Exp3 generally improves the initial cloud conditions. The SEDI skill scores of the Exp3 are better than those of the Ref in 84% and 74% of the cases, when evaluated for cloud-free (0–1 octas) and cloudy conditions (7–8 octas), respectively.

However, evaluation of the solar radiation forecasts shows somewhat ambiguous results. The Exp3 shows improved radiation histograms for relatively high radiation values, while it overpredicts the number of cases with low solar radiation. Veen (2013) cautioned that sometimes his method may cause too thick clouds (both optically and physically). The fact that the present Exp3 shows improved cloud fraction skill scores in conjunction with too many cases of low solar radiation values (Figure 10) may indicate that too thick clouds are also present in

the Exp3. It is worthwhile noting that as regards the effect on solar radiation, it is fundamentally more difficult to add clouds than to remove them; when removing clouds, it is clear that the cloud optical depth should become zero, while when adding clouds, it is non-trivial to reach the correct optical depth.

The overprediction of the number of low solar radiation cases is also consistent with an overall shift toward colder 2 m temperatures in the Exp3 as compared with the Ref. Similarly, also Veen (2013) found reduced daytime 2 m temperatures in his cloud initialization experiments. In the present study, both the Exp1 and Exp2 exhibit colder 2 m temperatures than the Exp3, indicating that the development steps of the methodology implemented in the Exp3 improve the performance as regards near-surface temperature.

The present working hypothesis for the future is first to improve the cloud-base estimates, especially for low clouds. We will develop a method to combine a “first guess” from the HARMONIE forecast model, together with satellite data and surface observations of cloud base. In addition, we will investigate how to improve the cloud-forming sensitivity technique. These proposed developments will aim to improve the short-term forecasts, for example, nowcasting, to be run and verified in near real time within the MetCoOp operational forecast environment.

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